ENVE 576
Indoor Air Pollution
Spring 2013

Lecture 1: January 17, 2013
(rescheduled from Jan. 15)
Course introduction

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Today's objectives

- Introduce the course
- Introduce myself
- Introduce yourselves
- Discuss syllabus
  - Course information, outline, schedule, ground rules
  - Why are we all here?

- Introduce the course, topics, and field of indoor air
  - Time activity and human exposure
  - Indoor and outdoor atmospheres
  - Fundamental air principles

About me

- B.S.E., Civil Engineering
  - Tennessee Technological University, 2007
- M.S.E., Environmental and Water Resources Engineering
  - The University of Texas at Austin, 2009
  - Thesis: "Energy implications of filtration in residential and light-commercial buildings"
- Ph.D. Civil Engineering
  - The University of Texas at Austin, 2012
  - Dissertation: "Characterizing the impacts of air-conditioning systems, filters, and building envelopes on exposures to indoor pollutants and energy consumption in residential and light-commercial buildings"
- Second time teaching a full course
  - First time for this particular course
  - Learning experience for everyone (and I mean ***everyone***)

Course information

ENVE 576: Indoor Air Pollution

Course Unique Number(s)

- Section 1: 24899 (in class)
- Section 2: 25173 (online)

Classroom and Meeting Time

- Stuart Building 220
- Tuesday nights, 5:00 PM – 7:40 PM

Prerequisites

- ENVE 405 - *I don't even know what this is*
- ENVE 520 - Environmental Monitoring and Assessment
  - Very flexible on prerequisites

Course information

Course Catalog Official Description

- Indoor air pollution sources, indoor pollutant levels, monitoring instruments and designs; indoor pollution control strategies: source control, control equipment and ventilation; energy conservation and indoor air pollution; exposure studies and population time budgets; effects of indoor air population; risk analysis; models for predicting source emission rates and their impact on indoor air environments.

Course objectives (in my own words)

To introduce students to important concepts of indoor airborne pollutants, including their physical and chemical properties, emission sources, and removal mechanisms. By taking this course students will be able to:

1. Describe particle-phase, gas-phase, and biological pollutants found in indoor environments
2. Model indoor pollutant emission, transport, and control
3. Manipulate and perform calculations with aerosol distributions and gas-phase compounds
4. Analyze indoor pollutant control technologies and determine their effectiveness
5. Read and critically analyze articles in the technical literature on indoor air pollution
6. Prepare and review written and oral technical communication

Textbook and reading materials

- There is no textbook for this course

- I rely on a mixture of notes from various textbooks and technical papers and publications
  - As well as notes from my previous courses at UT-Austin

I will draw from several reference texts, in case you are interested:

- Hinds, W. C., *Aerosol technology: Properties, behavior, and measurement of airborne particles*, Wiley (1999)
- Morawska, L. and Salthammer, T., *Indoor environment: airborne particles and settled dust*, Wiley-VCH (2003)
- Salthammer, T. and Uhde, E., *Organic Indoor Air Pollutants: occurrence, measurement, evaluation*, Wiley-VCH (2009)
- Seinfeld, J. H. and Pandis, S. N., *Atmospheric chemistry and physics: from air pollution to climate change*, Wiley (2006)
- Spengler, J., McCarthy, J., and Samet, J. *Indoor air quality handbook*, McGraw-Hill Professional (2001)

Textbook and reading materials

- In our syllabus I've also listed about 30 research articles and other documents that I will utilize in class
  - These are all labeled "suggested readings"
  - That means you don't have to read them
    - They mostly provide a place for those interested in learning more

- I use these articles to inform the core of each lecture
  - But also rely on many others that aren't listed

- Every once in a while I will ask that you do read a particular article
  - I'll let you know

Course topics

- Introduction: Human exposure, indoor and outdoor atmospheres
- Reactor models, ventilation, and human exposure patterns
- Pollutant types and sources
- Gaseous pollutants (VOCs and others)
  - Sources, adsorption/desorption, emission models, reactive deposition, homogeneous chemistry, byproduct formation
- Particulate matter
  - Single particle physics, particle size distributions, respiratory deposition, sources, surface deposition and resuspension, filtration and air cleaners
- Biological matter
  - Dust, pollen, mold, microbes
- Semi-volatile organic compounds (SVOCs)
  - Pesticides, flame retardants, etc.
- Measurement techniques and sampling campaigns
- Health effects: epidemiology and physiological responses
- Infectious disease transmission and risk
- IAQ in developing countries
- Applications: standards and manufacturer ratings

About you

- Who are you?
  - First and last name
  - Where are you from?
- What is your primary degree emphasis?
  - Undergraduate or graduate?
  - Engineering or other?
  - If graduate, masters or PhD?
    - Doing research? If so, what is your research topic?
- Why are you taking this course?
- Any relevant work and/or research experiences?

Course expectations

- Graduate course
  - Big focus on research and peer-reviewed literature
- Grading
  - Homework
    - Several HW assignments throughout semester (up to 6)
  - Exam(s)
    - One (*likely*) take-home exam will be given in early March
    - No final exam scheduled
  - Project
    - A major deliverable in this course will be one final project
    - Research report on indoor air pollution
      - Will involve measurement and/or modeling of some pollutant in some indoor environment
      - Very flexible, and you will have a few weeks to decide
    - Some HW assignments may also be combined into a mini project

Course grading

• HW	30%
• Take-home exam	30%
• Final project	40%
• Total	100%

Grading scale
A ≥ 900 (90%)
B 800-899 (80-89.9%)
C 700-799 (70-79.9%)
D or below <699 (<69.9%)

A note on research project expectations

- Your research project will be very much like a conference paper or journal article
  - For those already doing research, this gives you a chance to get something more out of your coursework
  - Or alternatively, a chance to get away from your thesis work!

- The purpose is to introduce a topic, survey the peer reviewed literature, describe your methods of calculation and/or measurement, show your results, discuss them, and conclude
  - Every once in a while a student will have something strong enough for a publication

- More on this later today and throughout the course

Course website

- I will post lecture notes and updated syllabus on our course website:
  - http://built-envi.com/courses/enve-576-iap-sp13/
  - I will do so always just before class (within ~1 hour usually)
    - I will try to post earlier, but judging from last year, I'm not very good at it!

- I will also use Blackboard for:
  - Updated syllabus/schedule/suggested reading assignments
  - Lecture notes
  - Reading materials
    - Should be about 30 articles already uploaded now and available for download
    - Is that true?
  - Assignments
  - Grades

- I generally communicate with the class via mass email
  - Don't let me go into your spam folder!
  - Do you have a different email address that you prefer?
    - If so, email me at brent@iit.edu

Tentative schedule (always changing)

Tentative Course Schedule

Week	Date	Lecture Topics	Reading*	Due date for:
1	Jan 15	Introduction to topic/field • Time activity and human exposure • Indoor and outdoor atmospheres • Fundamental air principles	1–3	
2	Jan 22	Reactor models • Steady-state and dynamic Ventilation and air exchange rates Human exposure patterns • Inhalation and intake fractions	4–6	
3	Jan 29	Overview of indoor pollutants • Particulate matter • Gas-phase compounds ⇒ Organic and inorganic Biological	7	HW1
4	Feb 5	Gaseous pollutants • Sources • Adsorption/desorption Emission models	8–11	HW2
5	Feb 12	Gaseous pollutants • Reactive surface deposition • Homogenous chemistry • Byproduct formation (incl. SOA)	12–14	HW3
6	Feb 19	Particulate matter • Single particle physics • Particle size distributions • Respiratory deposition	15–17	
7	Feb 26	Particulate matter • Particle sources (indoor and outdoor) • Deposition and resuspension	18–20	HW4
8	Mar 5	Particulate matter • Filtration and air cleaners	21–23	Exam assigned
9	Mar 12	Biological pollutants • Dust, pollen, mold, bacteria SVOCs	24,25	Exam due
10	Mar 19	No class - Spring break		
11	Mar 26	Measurement technologies		
12	April 2	Health effects • Epidemiology Physiological responses	26,27	HW5
13	April 9	Infectious disease transmission and risk		
14	April 16	Developing countries	28–30	HW6
15	April 23	Applications • Standards and manufacturer ratings	31–33	
16	April 30	Final presentations		Final project
Final	TBD	No final exam		

Any questions thus far?

Introduction to field and topic of indoor air

- Why do we study indoor air?

- We spend most of our time indoors
  - Nearly 90% of the time, on average in the developed world
  - Approximately 18 hours indoors for every 1 hour outdoors

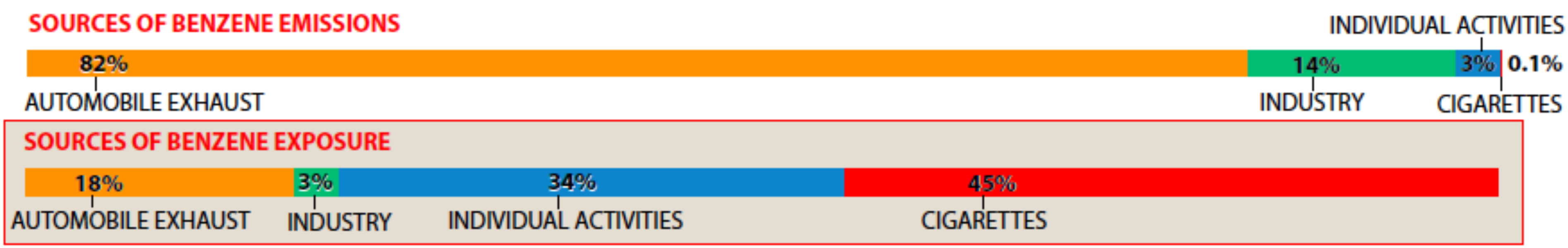
- We bring materials, furnishings, appliances, and activities into buildings, most of which emit/release a variety of substances
  - Some harmful, some not

- Buildings also exchange air without the outdoors
  - Outdoor air pollution becomes indoor air pollution
  - Indoor pollution becomes outdoor pollution

- Indoor air is a dominant environmental exposure
  - More than half of the body's intake of air is done so inside inside homes
  - 80-90% inhaled in buildings generally

Why do we study indoor air?

- Indoor concentrations of most pollutants are higher than outside
  - Global average of ~3:1 indoor/outdoor ratio
    - Huge variability between pollutants
- Increasing number of indoor diseases/health effects
- We keep sensitive equipment/precious artifacts inside
- We regulate outdoor air based on emissions
  - No indoor air regulations
    - Other than smoking bans and product emission controls at manufacture stage
  - Disconnect between emissions and exposure
    - Benzene example (outdoor sources include auto exhaust and industry):



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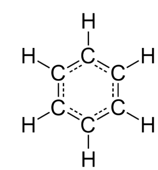


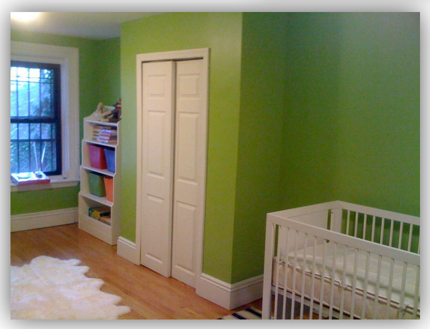
Ott and Roberts, 1998 *Scientific American*

History of indoor air

- Since there has been shelter, indoor air has been important
- Greeks and Romans (400 BC) knew of adverse effects of polluted air in crowded cities and mines
- The Bible mentions living in damp (moist) buildings was linked to lepros
  - Bacterial infection
- Crowded cities and chimney sweeps in 1600s and 1700s highlighted the importance of air pollution indoors and outdoors
- In the 1800s, slaves and prisoners died in very small, poorly ventilated rooms
  - Providing evidence of the important of ventilation
- Also “bad air” blamed for the spread of disease
  - “deficient ventilation … (is) more fatal than all other causes put together,” 1850
- Now, in developed regions of the world, buildings have vented cooking appliances with generally clean fuels, central heating and air-conditioning, new furnishings and materials, lower ventilation rates
  - And a relatively high prevalence of allergies, asthma, and other health issues
- In developing regions of the world we still have burning of biomass on inefficient and unvented stoves
  - And a high prevalence of respiratory disease and other health effects

Sundell, 2004 *Indoor Air*

Modern indoor environments

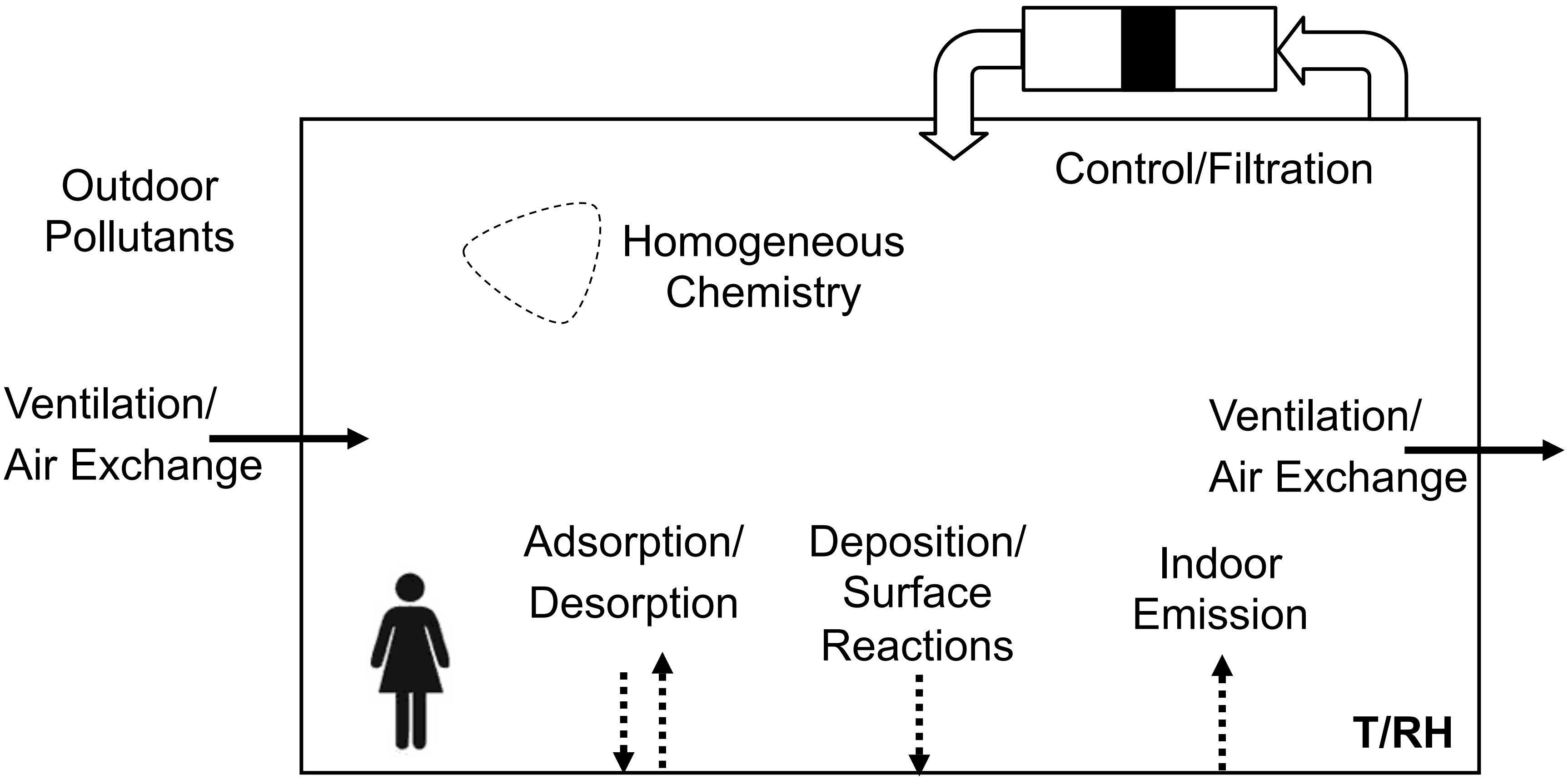


Types of indoor emission sources

- Building materials
  - Wood and composite wood
  - Gypsum wallboard
  - Concrete
  - Carpet
  - Vinyl flooring
- Furnishings
  - Bedding
  - Tables
  - Couches/chairs
  - Drapes
- Architectural coatings
  - Paints
  - Stains
  - Varnishes
- Consumer products
  - Cleaners
  - Fragrances
  - Personal care products
- Combustion
  - Cigarettes, cigars, pipes
  - Gas stoves
  - Space heaters
  - Candles
  - Incense
- Electronic equipment
  - Laser printers
  - Computers
  - Photocopiers
- Volatilization from water
- Soil vapor intrusion
- People, pets, insects

Modern indoor environments

To understand the levels of airborne pollutants that we are exposed to, we need to understand the underlying physical, chemical, and biological mechanisms that drive pollutant emission, transport, and control



Some important classes of indoor pollutants

- Inorganic gases
  - CO, NO_2, O_3, NH_3, H_2S, SO_2
- Organic gases (my partition to solids, binding to particles)
  - Volatile organic compounds (hundreds of these)
  - Semi-volatile organic compounds (SVOCs)
  - Carbonyls
  - Acids
  - Radicals
- Particulate matter
  - Size, shape, mass, constituents (e.g., metals)
- Radioactive gases and particles
- Microbiological
  - Bacteria, viruses, molds, mildew, fungi, dander

Indoor air physics and chemistry

- Indoor air physics and chemistry is much like outdoor air physics and chemistry
  - With a few important exceptions
- Indoor atmospheres constitute a very small fraction of the planetary atmosphere
  - However, most of that air is breathed by humans on a daily basis

Table 1
Some attributes of the global, urban, and indoor atmospheres[a]

Environment	Mass (kg)	Flow, F ($kg\,d^{-1}$)	Mass breathed, Q^b ($kg\,d^{-1}$)	Ratio, $Q:F$
Global atmosphere	5×10^{18}	—	$\sim 10^{11}$	—
Urban atmospheres	$\sim 10^{15}$	$\sim 3 \times 10^{15}$	$\sim 4 \times 10^{10}$	$\sim 10^{-5}$
Indoor atmospheres	$\sim 10^{12}$	$\sim 10^{13}$	$\sim 8 \times 10^{10}$	$\sim 10^{-2}$

[a] For the urban and indoor atmospheres, attributes are summed over all environments on earth.

[b] For the global and urban atmospheres, the mass breathed includes air inside and outside of buildings.

Nazaroff, Weschler, and Corsi 2003 *Atmospheric Environment*

Indoor air physics and chemistry

Table 2
Some attributes of urban and indoor atmospheres

Parameter	Urban atmosphere	Indoor atmosphere
Residence time	$\sim 10\,\mathrm{h}$	$\sim 1\,\mathrm{h}$
Light-energy flux	$\sim 1000\,\mathrm{W\,m^{-2}}$ (daytime)	$\sim 1\,\mathrm{W\,m^{-2}}$
Surface-volume ratio	$\sim 0.01\,\mathrm{m^2\,m^{-3}}$	$\sim 3\,\mathrm{m^2\,m^{-3}}$
Precipitation	~ 10–$150\,\mathrm{cm\,year^{-1}}$	Absent

- Residence times are lower indoors than outdoors
- Sunlight is much much lower indoors than outdoors
- Surface-to-volume ratios are much much higher indoors
- There is no precipitation indoors (hopefully)

Nazaroff, Weschler, and Corsi 2003 *Atmospheric Environment*

Exposure science

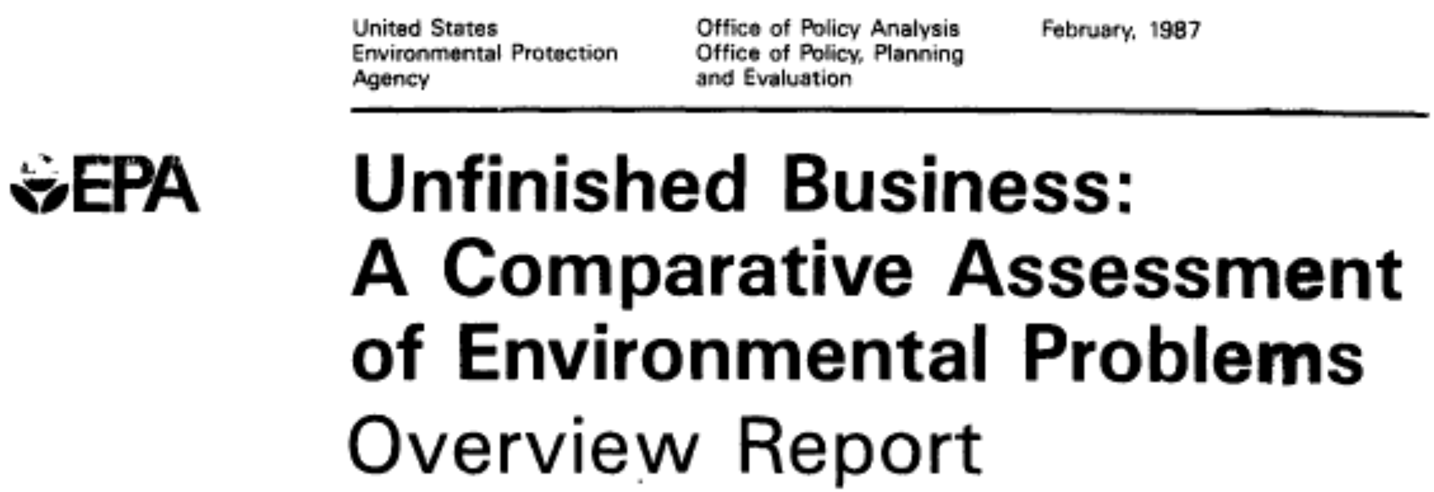
- A closely related field is "exposure science"
  - Bridge between physical sciences/engineering and health sciences
  - How much of which pollutants are humans exposed to?
    - How and where do they come in contact with the body?

- Exposure pathways
  - Ingestion, inhalation, dermal uptake, ocular (eyes), hands

- Inhalation exposure
  - Adults inhale 15-20 m^3 of air per day
  - Adults ingest 1.2 L per day of water, or 0.0012 m^3/day
    - Adults ingest about ~16000 times as much air as water per day!
  - Water is about 800 times as dense as air, so humans ingest about 18 times more mass of air than water per day
  - The point is that we put large amounts of air into our bodies every day by inhalation!
    - So what pollutants are contained in air are important!

What are the risks of indoor air pollution?

- In 1987, the US Environmental Protection Agency (EPA) published a report on the population-wide impacts of environmental problems
  - Health effects in humans (cancer and non-cancer)
  - Ecological impacts
  - Impacts on human welfare



United States Environmental Protection Agency

Office of Policy Analysis
Office of Policy, Planning and Evaluation

February, 1987

EPA

Unfinished Business:
A Comparative Assessment of Environmental Problems
Overview Report

http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000BZOP.txt

US EPA population cancer risks, 1987

1. (tie) Worker exposure to chemicals
1. (tie) Indoor radon
3. Pesticide residue on foods
4. (tie) Indoor air pollutants (non-radon)
4. (tie) Consumer exposure to chemicals
   (includes cleaning fluids, particleboard, asbestos products)
6. Hazardous/toxic outdoor air pollutants (from industry)
7. Depletion of stratospheric ozone
8. Hazardous waste sites (inactive)
9. Drinking water (radon and THMs)
10. Application of pesticides
11. Radiation other than indoor radon

12-29. Others, including groundwater contamination at 21 and criteria air pollutants at 22

http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000BZOP.txt

US EPA population non-cancer risks, 1987

- "High" non-cancer risks
  - Criteria air pollutants (e.g., $PM_{2.5}$, O_3, NO_2, Pb)
  - Hazardous air pollutants
  - Indoor air pollutants (not radon)
  - Drinking water
  - Accidental toxic releases
  - Pesticides on food and application of pesticides

Indoor Air Pollution Other Than Radon

Comments

Important health problem, although not generally recognized as such by the public. For a variety of reasons (statutory, multitude of sources, difficulty of control, etc.), this has not been a major EPA priority.

http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000BZOP.txt

Costs of poor IAQ/ventilation

- Health and productivity gains from better indoor environments in the U.S.
  - Fisk (2000) *Annual Reviews of Energy and Environment*
  - $6-14 billion from reduced respiratory disease
  - $1-4 billion from reduced allergies and asthma
  - $10-30 billion from reduced sick building syndrome
  - $20-160 billion from direct improvements in worker performance
- $37-208 billion annual savings possible
  - Fisk (2002) *ASHRAE Journal*
- Improved ventilation in a manufacturing facility led to reduced sick days
  - Milton et al. (2000) *Indoor Air*
- Increased ventilation led to slight increase (5%) in productivity
  - Wargocki et al. (2000) *Indoor Air*

Methods of studying indoor air pollution

- Indoor air quality (IAQ) isn't really a standalone discipline
  - Involves engineers, public health officials, architects, contractors, medical professionals, epidemiologists, academics, biologists, psychologists, economists, etc.
  - Many different approaches

- The big picture is that:
  - We are interested in concentrations of pollutants and human exposures
    - Worker productivity/safety
    - Health effects
    - Material degradation
    - Biological growth/disinfection
  - So we need to use and convert concentrations and conduct mass balances to get concentrations, exposures, and doses
    - And to determine what affects those

Who studies indoor air?

- National/state institutions
  - US EPA http://www.epa.gov/iaq/
  - NIOSH/CDC http://www.cdc.gov/niosh/topics/indoorenv/
  - NIST http://www.nist.gov/indoor-air-quality.cfm
  - NRC-Canada http://www.nrc-cnrc.gc.ca/eng/solutions/facilities/indoor_environment.html
  - CARB http://www.arb.ca.gov/research/indoor/indoor.htm
  - LBNL http://energy.lbl.gov/ie/

- Universities
  - Harvard, Berkeley, Syracuse, Rutgers, University of Texas at Austin, Penn State, Drexel, Clarkson, Purdue, … IIT!
  - Danish Technical University, Tsinghua, National University of Singapore
    - Many others

Who studies indoor air?

- Standards organizations and professional societies
  - ISIAQ (International Society of Indoor Air Quality and Climate)
  - ISES (International Society of Exposure Science)
  - AAAR (American Association for Aerosol Research)
  - ASHRAE (American Soc. of Heating, Refrigerating, and Air-Conditioning Eng.)
  - IAQA (Indoor Air Quality Association)
  - AIHA (American Industrial Hygiene Association)

- Important journals
  - *Indoor Air*
  - *Building and Environment*
  - *Atmospheric Environment*
  - *Environmental Health Perspectives*
  - *Environmental Science and Technology*
  - *Journal of Exposure Science and Environmental Epidemiology*
  - *HVAC&R Research*
  - *Environmental Pollution*
  - *Aerosol Science and Technology*

FUNDAMENTAL AIR PRINCIPLES

What is "air"?

- What chemical species are in "clean" air?

Species	MW (g/mol)	%
Nitrogen (N_2)	28	78.1%
Oxygen (O_2)	32	20.9%
Argon (Ar)	40	0.9%
Water (H_2O)	18	0.1-3% (highly variable)
Carbon dioxide (CO_2)	44	0.04% (400 ppm)*
Neon (Ne)	20	0.0018% (18 ppm)
Helium (He)	4	0.0005% (5 ppm)

* Can reach 5000 ppm (0.5%) or more indoors

What is "air"?

- What chemical species are in "polluted" air?

Species	MW (g/mol)	%
Nitrogen (N_2)	28	78.1%
Oxygen (O_2)	32	20.9%
Argon (Ar)	40	0.9%
Water (H_2O)	18	0.1-3% (highly variable)
Carbon dioxide (CO_2)	44	0.04% (400 ppm)*
Neon (Ne)	20	0.0018% (18 ppm)
Helium (He)	4	0.0005% (5 ppm)
Methane (CH_4)	16	0.0002% (2 ppm)
Krypton (Kr)	84	0.0001% (1 ppm)
Hydrogen (H_2)	2	0.00006% (0.6 ppm)
xyz pollutant	depends	< 300 **ppb** (0.00003%)**

* Can reach 5000 ppm (0.5%) or more indoors

** Highly variable

Air as an ideal gas

- Every gas in air acts as an ideal gas

$$PV = nRT$$ Ideal Gas Law (Boyle's law + Charles's law)

- Air as a composition of ideal gases
  - A bunch of ideal gases acting as an ideal gas
- For individual gases (e.g., N_2, O_2, Ar, H_2O, CO_2, pollutant *i*):

$$P_i V = n_i RT$$

P_i = partial pressure exerted by gas *i*
n_i = # of moles of gas *i*
R, V, T = gas constant, volume, temperature

$$P_i = \frac{n_i}{V} RT$$

Rearrange so that n_i/V is the molar concentration

$$P_i = y_i P_{tot}$$

P_{tot} = total pressure of air (atm, Pa, etc.)
y_i = mole fraction of gas *i* in air (moles *i* / moles air)

Air as an ideal gas

- Air as a composite mixture

$$P_i = y_i P_{tot}$$

$$P_{tot} = \sum P_i = \sum \frac{n_i}{V} RT = \frac{RT}{V} \sum n_i = \frac{RT}{V} n_{tot}$$

$$PV = nRT$$

Density of air

$$PV = nRT \longrightarrow \frac{n}{V} = \frac{P}{RT}$$

$$\frac{n}{V} = \frac{P}{RT} = \frac{1 \text{ atm}}{\left(82.05 \times 10^{-6} \ \frac{\text{atm} \cdot \text{m}^3}{\text{mol} \cdot \text{K}}\right) \times 293 \text{ K}}$$

20C, 68F

$$\frac{n}{V} = 41.6 \ \frac{\text{moles}}{\text{m}^3} = 0.0416 \ \frac{\text{moles}}{\text{L}}$$

$$\rho_{air} = MW_{air} \times 0.0416 \ \frac{\text{moles}}{\text{L}} \ @20 \text{ degrees C}$$

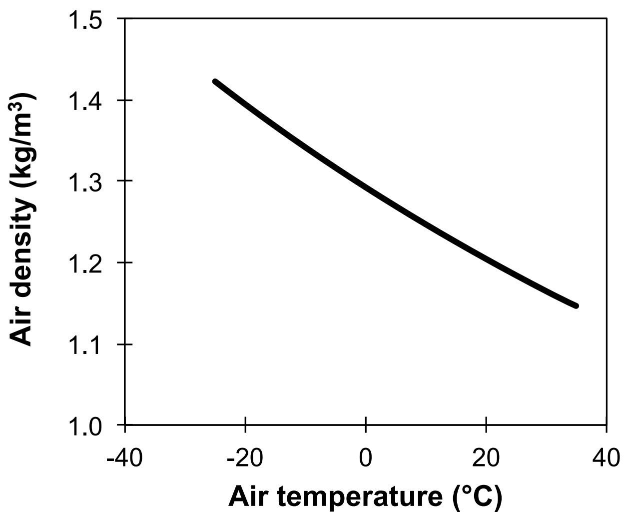
What is the molecular weight (MW) of air?

$$MW_{air} = \sum y_i MW_i = y_{N_2} MW_{N_2} + y_{O_2} MW_{O_2} + y_{H_2O} MW_{H_2O} + \ldots$$

$$MW_{air} = 0.781(28 \text{ g/mol}) + 0.209(32 \text{ g/mol}) + \ldots = 29 \text{ g/mol}$$

$$\rho_{air} = (29 \ \frac{\text{g}}{\text{mol}}) \times 0.0416 \ \frac{\text{mol}}{\text{L}} = 1.2 \ \frac{\text{g}}{\text{L}} = 1.2 \ \frac{\text{kg}}{\text{m}^3} \ @20 \text{ degrees C}$$

Hang on to this number: density of air is ~1.2 kg/m^3 at 20°C



$$\rho_{air} \approx 1.3 - 0.0046(T_{air}) \text{ where } T_{air} \text{ is in degrees C}$$

Units of measurement for air pollutants

- **Number concentrations** (# per volume of air, #/m^3)
  - # of molecules per m^3 (highly reactive species, e.g., OH radical)
  - # of particles per m^3 (particulate matter)
  - # of cells or colony forming units per m^3 (biological)
- **Mass concentrations** (mass per volume of air)
  - ng/m^3 typical for metals and for SVOCs
  - µg/m^3 typical for indoor VOCs and particulate matter
  - mg/m^3 big sources, e.g., ETS, cooking, industrial hygiene
- **Molar concentrations** (variations on $y_i = \mathrm{mol}_i/\mathrm{mol}_{air}$)
  - Mole fraction (y_i) = mol/mol
  - % concentration = moles per 100 moles = 100*y_i
  - Parts per million by volume (ppm$_v$) (or just ppm in this course)

$$1 \text{ ppm} = \frac{1 \text{ mol of } i}{10^6 \text{ moles of air}} = 10^{-6} \frac{\text{moles of } i}{\text{moles of air}} = 10^{-6} * y_i$$

  - Parts per billion by volume (ppb$_v$) (or just ppb in this course)

$$1 \text{ ppb} = \frac{1 \text{ mol of } i}{10^9 \text{ moles of air}} = 10^{-9} \frac{\text{moles of } i}{\text{moles of air}} = 10^{-9} * y_i$$

Units of measurement

- Conversion between mass and volume concentrations

$$1 \text{ ppb} = \frac{1 \text{ mol of } i}{10^9 \text{ moles of air}} = 10^{-9} \frac{\text{moles of } i}{\text{moles of air}}$$

- If we multiply y_i by MW of pollutant, moles/L of air, and conversion factors:

$$10^{-9} \frac{\text{moles of } i}{\text{moles of air}} * MW_i \left(\frac{\text{g of } i}{\text{moles of } i} \right) * \underbrace{\left(\frac{\text{moles of air}}{24 \text{ L}} \right)}_{\frac{V}{n} = \left(\frac{n}{V}\right)^{-1} = \left(0.0416 \frac{\text{moles}}{\text{L}}\right)^{-1} = 24 \frac{\text{L}}{\text{mole}} \text{ @20 degrees C}} * 10^6 \frac{\mu\text{g}}{\text{g}} * 10^3 \frac{\text{L}}{\text{m}^3}$$

- Then:

$$\# \text{ of } \frac{\mu\text{g}}{\text{m}^3} = \# \text{ of ppb} * \frac{MW_i}{24} = \# \text{ of ppb} * \frac{MW_i P}{RT}$$

$$\# \text{ of } \frac{\text{mg}}{\text{m}^3} = \# \text{ of ppm} * \frac{MW_i}{24} = \# \text{ of ppm} * \frac{MW_i P}{RT}$$

Unit conversion example

- What mass concentration for ozone corresponds to 120 ppb?
  - At 20 degrees C (68 degrees F)

$$\#\ \text{of}\ \frac{\mu\text{g}}{\text{m}^3} = \#\ \text{of ppb} * \frac{MW_i}{24} = \#\ \text{of ppb} * \frac{MW_i P}{RT}$$

$$MW_{ozone} = 48\ \text{g/mol}$$

$$\#\ \text{of}\ \frac{\mu\text{g}}{\text{m}^3} = 120\ \text{ppb} * \frac{48}{24} = 240\frac{\mu\text{g}}{\text{m}^3}$$

Unit conversion example

- What mass concentration for ozone corresponds to 120 ppb?

$$MW_{ozone} = 48 \text{ g/mol} \qquad \# \text{ of } \frac{\mu g}{m^3} = 120 \text{ ppb} * \frac{48}{24} = 240 \frac{\mu g}{m^3} \quad @\ 20°C$$

  - What if T rises to 100 degrees F (38 degrees C)?
    - 311 K

$$\# \text{ of } \frac{\mu g}{m^3} = \# \text{ of ppb} * \frac{MW_i P}{RT} = \frac{120 \text{ mol}}{10^9 \text{ mol}} * \frac{(48 \ \frac{g}{mol}) * 1 \text{ atm}}{8.205 \times 10^{-5} \frac{m^3 \cdot atm}{mol \cdot K} * 311 \text{ K}} * \frac{10^6 \ \mu g}{g} = 225 \ \frac{\mu g}{m^3}$$

- Effects of temperature:
  - When using ppm and ppb (mol/mol), T doesn't affect concentration
  - When using mass concentrations, if T ↑ RT ↑ mass concentration (m/V) ↓

Unit conversions summary

- Indoors we can usually get away with:
  - Air density = 1.2 kg/m^3

$$\#\ \text{of}\ \frac{\mu\text{g}}{\text{m}^3} = \#\ \text{of ppb} * \frac{MW_i}{24}$$

$$\#\ \text{of}\ \frac{\text{mg}}{\text{m}^3} = \#\ \text{of ppm} * \frac{MW_i}{24}$$

  - Temperatures rarely deviate from 60-80 F (15-27 C)
    - 288-300 K

Role of water vapor in air

- Relative humidity $$RH = \frac{P_w}{P_{w,sat}}(T)$$

- Where can you get $P_{w,s}$?

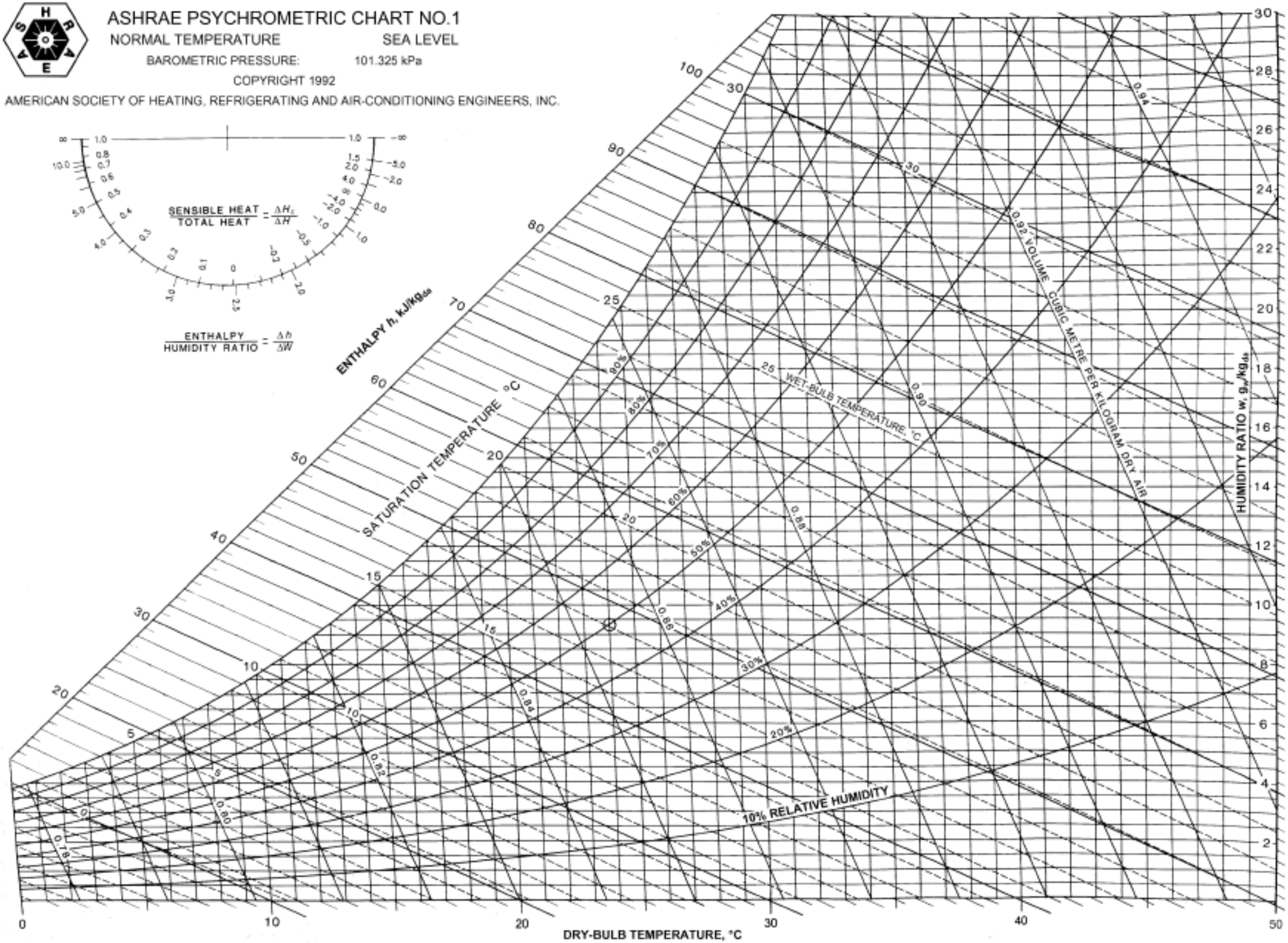
$$\ln p_{ws} = C_8/T + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln T$$

where

$C_8 = -5.800\,220\,6\ \mathrm{E}{+}03$
$C_9 = 1.391\,499\,3\ \mathrm{E}{+}00$
$C_{10} = -4.864\,023\,9\ \mathrm{E}{-}02$
$C_{11} = 4.176\,476\,8\ \mathrm{E}{-}05$
$C_{12} = -1.445\,209\,3\ \mathrm{E}{-}08$
$C_{13} = 6.545\,967\,3\ \mathrm{E}{+}00$

p_{ws} = saturation pressure, Pa
T = absolute temperature, K = °C + 273.15

ASHRAE Handbook of Fundamentals
Equation or chart


ASHRAE PSYCHROMETRIC CHART NO.1
NORMAL TEMPERATURE
SEA LEVEL
BAROMETRIC PRESSURE: 101.325 kPa
COPYRIGHT 1992
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = $\Delta H_s / \Delta H$
ENTHALPY / HUMIDITY RATIO = $\Delta h / \Delta W$
ENTHALPY h, kJ/kg da
SATURATION TEMPERATURE °C
WET-BULB TEMPERATURE, °C
0.92 VOLUME CUBIC METRE PER KILOGRAM DRY AIR
HUMIDITY RATIO W, gw/kg da
10% RELATIVE HUMIDITY
DRY-BULB TEMPERATURE, °C

Psychrometric chart

- Need two quantities for a state point
  - Can get all other quantities from a state point

- Can do all calculations without a chart
  - Often require iteration
  - Many “digital” psychrometric charts available
    - Can make your own
  - Best source is *ASHRAE Fundamentals*

INDOOR AIR RESEARCH

Example class research projects

- Environmental tobacco smoke in hospitality venues before and after a smoking ban in Austin, Texas
  - By a colleague of mine: measurements in bars
  - Became a journal article in *J Expo Sci Environ Epidem*

- Contribution of wall cavity insulation to indoor contaminant levels
  - Modeling using previous literature, turned into conference paper

- Investigation of Chinese drywall in U.S. homes
  - Modeling using previous literature

- Particle exposure in a fire station in Austin, Texas
  - Measurement in a fire station

Project example: ETS in bars

- Measured occupancy and IAQ in 17 bars before and after a city-wide smoking ban in Austin, TX

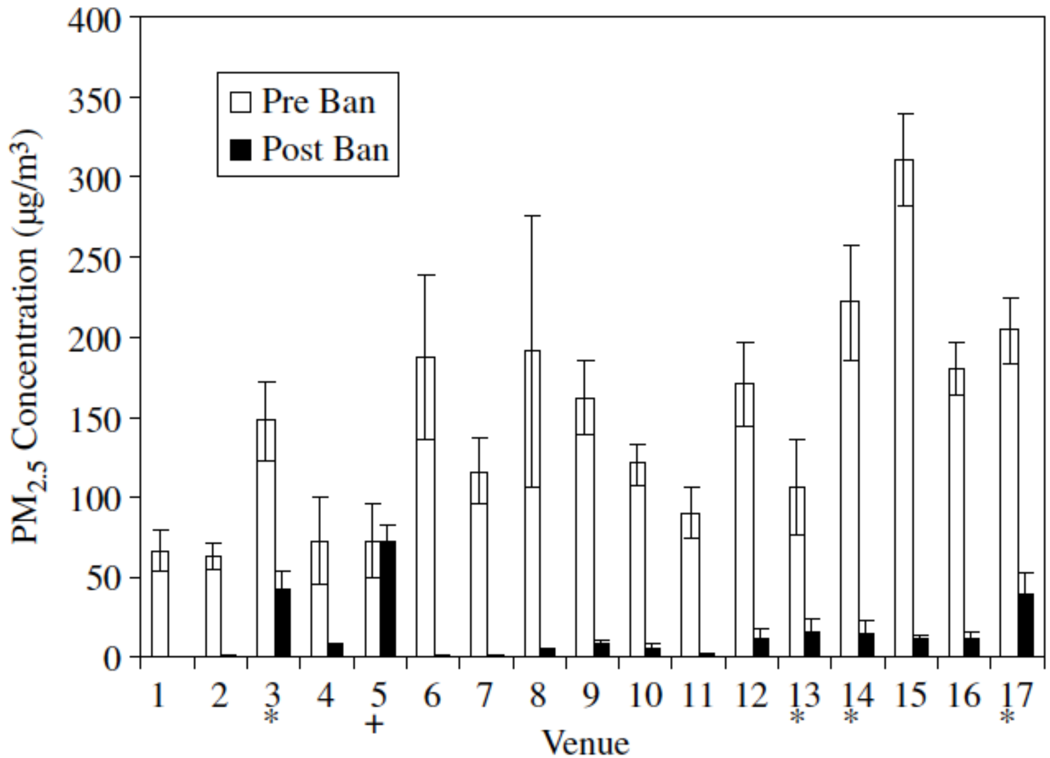


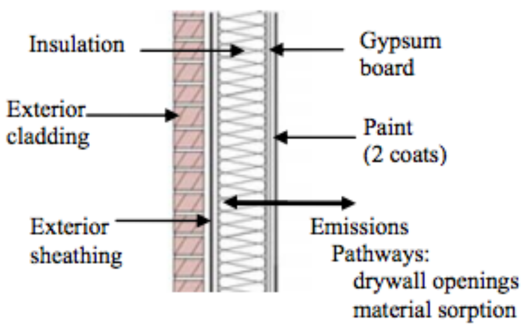
Figure 1. Best estimate pre- and post-ban $PM_{2.5}$ concentrations for all venues: *indicates occupant non-compliance and +indicates venues exempt from the ordinance.

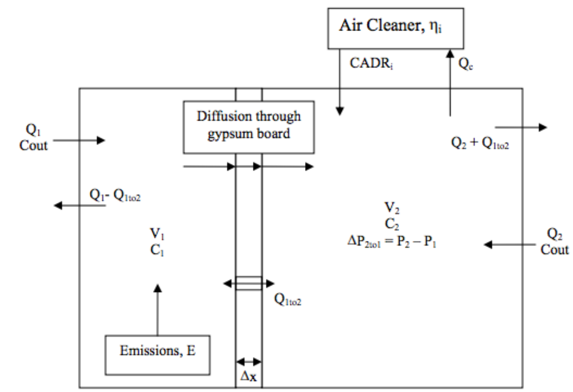
$PM_{2.5}$ concentrations decreased 71-99% in all venues

Waring and Siegel, 2006 *J Expo Sci Environ Epidem*

Project example: Emissions from insulation

- Modeled pollutant emission from insulation materials
  - Polyurethane foam, cellulose, fiberglass, cementitious foam





Polyurethane Spray-Foam		
	C_1 (µg/m3)	C_2 (µg/m3)
Pentamethyl dipropylenetriamine	435	212
Butylated Hydroxytoluene (BHT)	88	***43***

Fiberglass Batt		
	C_1 (µg/m3)	C_2 (µg/m3)
Nonanal	2	<1
Formaldehyde	22	***11***

Base Case Model Inputs
$\Delta P = -1$ Pa, $\lambda_1 = 1\ hr^{-1}$, $\lambda_2 = 0.5\ hr^{-1}$, wall opening = 0.0002 m^2/m^2, T=25°C

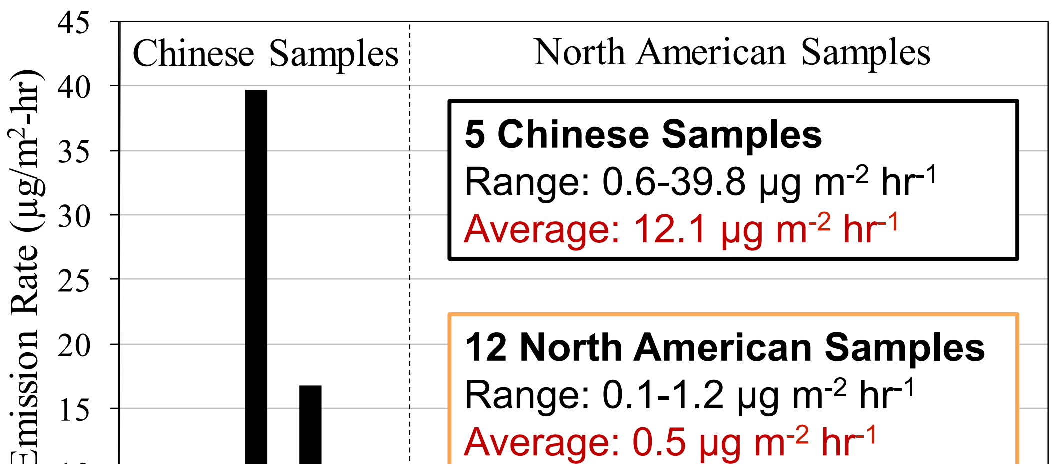
Blown-in Cellulose		
	C_1 (µg/m3)	C_2 (µg/m3)
Nonanal	6	3
Acetone	13	6
Formaldehyde	3	1
Hexanal	8	4
Toluene	1	1

Cementitious Foam		
	C_1 (µg/m3)	C_2 (µg/m3)
Glyoxal (ethanedial)	63	***31***

Jackson and Stephens, 2009 *Proc of Healthy Buildings*

Project example: Corrosive drywall emissions

- In 2009, tainted drywall (gypsum wallboard) materials were imported into the U.S. from China
  - Emitted pollutants into the indoor air, made people sick (nausea, headaches), smelled like rotten eggs, and corroded metals all around the homes
- At the time, lab and field samples were still being collected and the reports were still forthcoming
  - So I tried to model what the likely corrosive compound emission were



Hydrogen sulfide. Steady-state indoor concentrations of hydrogen sulfide exceed odor thresholds and recommended exposure levels in seven of the nine hypothetical conditions. Visible corrosion could likely occur within the period of one year in six of the hypothetical conditions. Even at low emission rates, hydrogen sulfide remains a potential culprit, especially in newly constructed tighter homes with low natural air exchange rates. Predicted hydrogen sulfide concentrations are likely to corrode copper, establish a sulfurous odor, and cause health effects include cough, nausea, and headache.

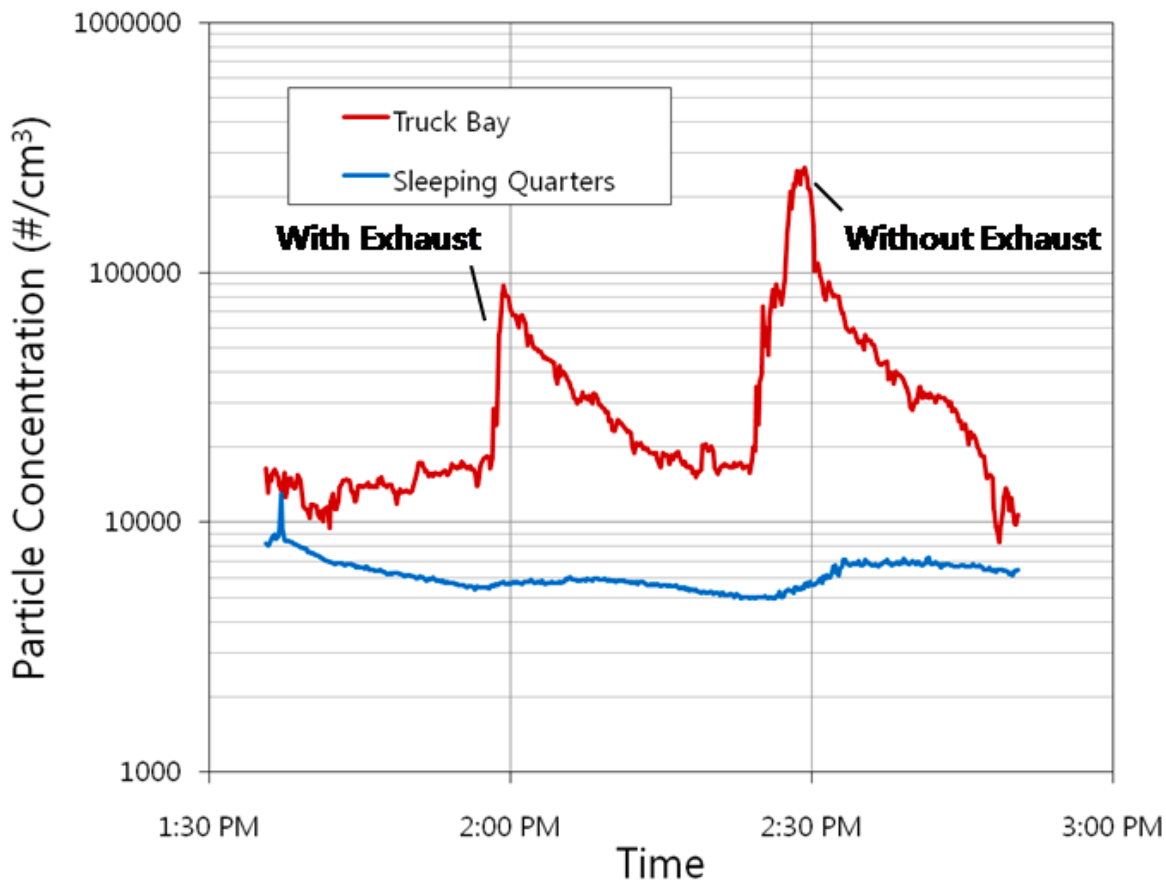
Project example: PM in fire stations

- Firefighters work, eat, sleep, and exercise during their 24 hour shifts
  - Right next to the diesel trucks that come in and out of the garage
  - Vents were installed a few years ago to expel diesel exhaust from garage
    - Do they work?

http://built-envi.com/submicron-particle-exposure-in-a-fire-station-in-austin-texas/

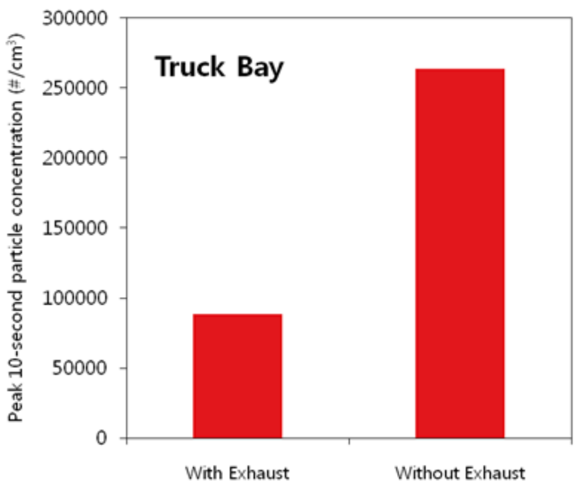
Project example: PM in fire stations

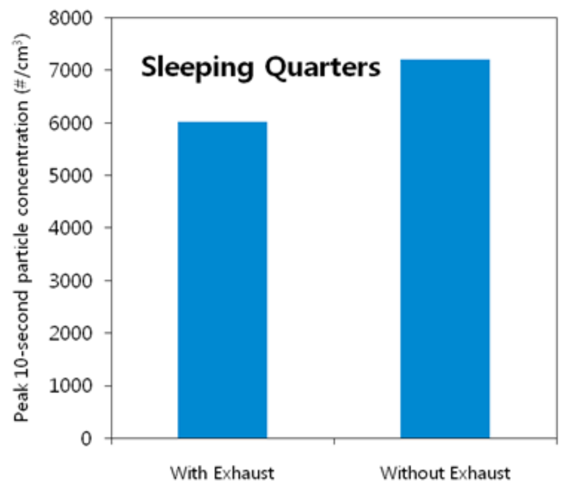
- Time-varying particle concentrations in the truck bay and upstairs sleeping quarters for one afternoon in 2012
  - With and without exhaust system installed



http://built-envi.com/submicron-particle-exposure-in-a-fire-station-in-austin-texas/

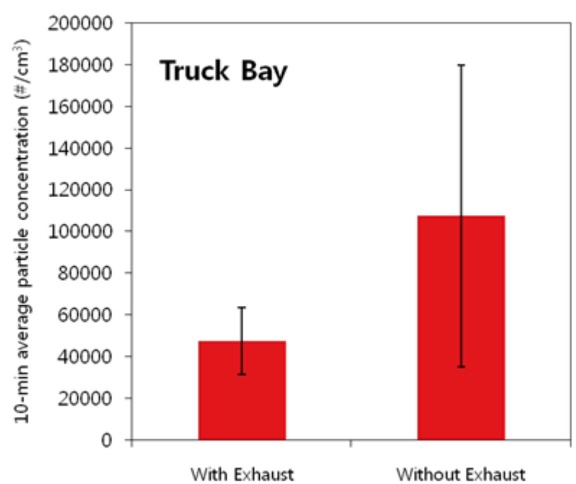
Project example: PM in fire stations

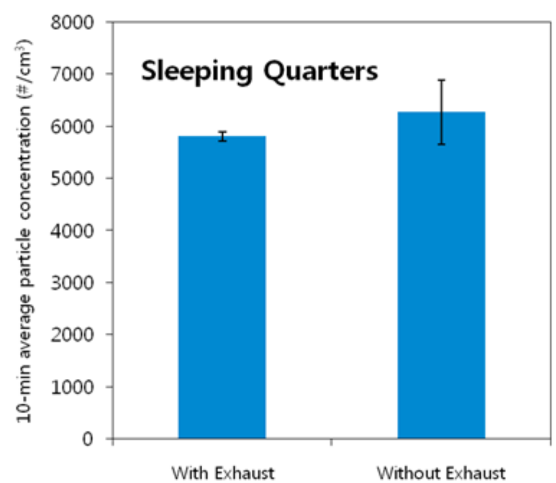




- 10-second peak concentrations in bay and sleeping quarters
  - w/ and w/out exhaust

- 10-minute average (+/- s.d.) concentrations in bay and sleeping quarters
  - w/ and w/out exhaust





http://built-envi.com/submicron-particle-exposure-in-a-fire-station-in-austin-texas/

Introduction to research

- Web of Science, Google Scholar, and others
  - http://library.iit.edu/databases/
- Accessing from off-campus
  - Example: http://scholar.google.com.ezproxy.gl.iit.edu/
- My own research publications
  - www.built-envi.com
- Citation managers
  - zotero: http://www.zotero.org/

Information for next lecture

- Back to the regularly scheduled time
  - Tuesday 5:00 to 7:40 pm

- Topics
  - Human exposure patterns
  - Reactor models
  - Ventilation and air exchange rates